

Test on the AGB Scenario as the Origin of the Extreme-Helium Population in ω Centauri

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10 April 2008

ABSTRACT

The most massive Galactic globular cluster, ω Centauri, appears to have multiple populations. Its bluest main sequence and extreme horizontal branch stars are suggested to have the common origin, that is, an extremely high helium abundance of $Y \sim 0.4$. The high helium abundance is most often attributed to asymptotic giant branch (AGB) stars. In this study we test the AGB hypothesis. We simulate the maximum-AGB models where the impact of AGB stars is maximised by assuming that supernova explosions do not affect the chemical evolution of the proto cloud. We compare the enrichment history of helium, metals, carbon and nitrogen to the observed values. Even under the most generous condition, the maximum-AGB models fail to reproduce the large values of helium $Y \sim 0.4$ and helium enrichment parameter $\Delta Y/\Delta Z \sim 70$ which were deduced from the colour-magnitude diagram fits. They also fail to reproduce the C and N contents of the blue population spectroscopically determined. We conclude that the AGB scenario with the canonical stellar evolution theory cannot explain the observational constraints and that the self chemical enrichment does not provide a viable solution. Alternative processes are desperately called for.

Key words: galaxies: globular clusters — individual (ω Centauri)

1 INTRODUCTION

The origin of the blue population in the most massive Galactic globular cluster (GC), ω Centauri, is at the centre of debate after the discovery of its multiple populations (e.g. Anderson 1997; Lee et al. 1999; Bedin et al. 2005). The explanation of the blue main sequence (bMS) of ω Cen by a huge excess of the primordial helium abundance, $\Delta Y \sim 1.2$, was implied via the colour-magnitude diagram (CMD) fitting (Norris 2004). This bMS, which contains ~ 30 percent of the cluster stars, is roughly 0.3 dex more metal-rich than the red main sequence (rMS) population (Piotto et al. 2005). Its blue colour despite its high metallicity is attributed to an extremely high value of helium. This explanation has further been reinforced by the fact that the same helium excess can reproduce the extended horizontal branch (EHB) of ω Cen (D’Antona & Caloi 2004; Lee et al. 2005). Follow-up spectroscopic and photometric investigations have been performed by many groups (e.g. Kayser et al. 2005; Sollima et al. 2006; Stanford et al. 2007; Villanova et al. 2007; van Loon et al. 2007). The extreme helium scenario appears to provide a successful solution to another cluster, NGC 2808, which also shows multiple main sequences (Piotto et al. 2007) and a pronounced EHB

(Lee et al. 2005). It has recently been claimed that the GCs with an EHB are among the most massive in the Milky Way, and the possible link between the mass of the cluster and the helium anomaly is heavily investigated on (Recio-Blanco et al. 2006; Lee et al. 2007). The existence of helium-rich GCs in the external galaxy, M 87, has also been suggested (Kaviraj et al. 2007), implying that this phenomenon may be universal.

The extreme helium scenario, however, has been criticised. This is mainly because the helium-enrichment parameter $\Delta Y/\Delta Z$ corresponding to proposed helium abundance ~ 70 or even higher, which is more than an order of magnitude larger than observational and theoretical values, $\Delta Y/\Delta Z = 1 - 5$ (e.g. Fernandes et al. 1996; Pagel & Portinari 1998; Jimenez et al. 2003). For possible origins for the extreme helium abundance, asymptotic giant branch (AGB) stars, massive stars, and Type II supernovae (SN II) have been widely discussed (Norris 2004; D’Antona et al. 2005; Maeder & Meynet 2006). Bekki & Norris (2006) however demonstrated that such candidates cannot produce the amount of helium required, for ordinary initial mass functions (IMFs) within the scheme of a closed-box self enrichment. More recently, Choi & Yi (2007) showed that essentially no population can

produce such a high value of $\Delta Y/\Delta Z$ via self-enrichment processes regardless of the shape of IMF.

Supernovae are not helpful for generating a high value of $\Delta Y/\Delta Z$ because they produce metals as well as helium. The ejecta from AGB stars is generally believed to show the largest helium enrichment parameters (e.g., see Izzard et al. 2004; Choi & Yi 2007). However, the AGB hypothesis is found to be unsuccessful for matching both the high helium abundance and the CNO properties constrained from observations even when the supernova effect is removed from the calculation (Karakas et al. 2006; Bekki et al. 2007).

We further elaborate on the works of Karakas et al. (2006); Bekki et al. (2007) by testing the *maximum-AGB hypothesis* where the impact of AGB stars is maximised by assuming that massive star ejecta of unknown mass range escape the small potential wells of proto clouds. In this letter we search for the parameter space that satisfies all the observational constraints including spectroscopic measurements.

2 THE CHEMICAL EVOLUTION MODELS

2.1 Introduction

We adopt the chemical enrichment code described in Choi & Yi (2007) following the formalism of Tinsley (1980). The two-component model assuming instant mixing and cooling traces the net metallicity Z , helium Y , carbon and nitrogen contents of the gas and stellar components.

The stellar mass, $M_s(t)$, and the cold gas mass, $M_g(t)$, are normalised to the initial system mass,

$$\mu_s(t) \equiv \frac{M_s(t)}{M_{tot}(0)}, \quad \mu_g(t) \equiv \frac{M_g(t)}{M_{tot}(0)}. \quad (1)$$

In this study, we assume that the formation of the former (rMS) population is essentially instant:

$$\psi(t \neq 0) = 0. \quad (2)$$

The evolution of the gas mass is given by

$$\frac{d\mu_g}{dt} = E(t) - \psi(t) \quad (3)$$

where the ejecta gas mass at time t , $E(t)$, is defined as

$$E(t) = \int_{m_t}^{m_{upper}} dm \phi(m) (m - w_m) \psi(t - \tau_m). \quad (4)$$

where $\phi(m)$ denotes the initial mass function (IMF), w_m the remnant mass for a star with main sequence mass m , τ_m the lifetime of a star of mass m , and m_{upper} the upper mass cut in the initial mass function. The Scalo IMF (Scalo 1986) with cutoffs at 0.1 and $100M_\odot$ is assumed, and the remnant mass w_m and the lifetime of a star τ_m are adopted from Ferreras & Silk (2000, 2001).

The equation for the evolution of metallicity in gas is given by

$$\frac{d(Z_g \mu_g)}{dt} = -\psi(t) + E_Z(t) \quad (5)$$

where the mass of ejected metal at time t , $E_Z(t)$, is defined as

$$E_Z(t) = \int_{m_t}^{m_{upper}} dm \phi(m) [m p_m \psi(t - \tau_m) + (m - w_m) \psi(t - \tau_m) Z_g(t - \tau_m)]. \quad (6)$$

where p_m denotes the newly synthesized and ejected metal (or helium, C, N) mass fraction to initial stellar mass. We will discuss this in greater detail in §2.2.

The initial chemical properties of the models are adopted from the observational values for the rMS population of ω Cen. The initial metallicity $Z_0 = 0.001$ and the initial C, O abundance $[C/M] = 0.0$, $[N/M] = 1.0$ are from the spectroscopic measurements of Piotto et al. (2005), and the initial helium abundance $Y_0 = 0.232$ is deduced from the CMD fit in Lee et al. (2005).

2.2 Chemical Yields

The chemical yields (p_m), defined as the mass fraction of a star of mass m that is *newly* converted to metals or helium and ejected, are the most important input parameter to the chemical evolution of a population. We basically adopt the helium, carbon and metal p_m predictions of Maeder (1992) for the mass range $9 - 100M_\odot$. For nitrogen, we adopt the p_m prediction of Nomoto et al. (1997). For $M_\odot \leq 6$ we adopt the helium, carbon, nitrogen, and metal yields from Herwig (2004). We confirm that the use of different yields (e.g. van den Hoek & Groenewegen 1997; Ventura et al. 2002) does not make any notable difference to our conclusion. We use the chemical yields from the hermitian fits to the p_m predictions. In Figure 1, we show the theoretical ejecta abundance predicted by our fitting functions from the metal-poor ($Z = 0.001$) stars of mass $0.1 - 100M_\odot$. The chemical abundances predicted and the resulting helium enrichment parameters are presented. As shown in the middle panel, the highest peak around $6M_\odot$ in the helium enrichment parameter diagram reaches the value proposed for the bMS population. Indeed, the AGB ejecta appears to be the most promising candidate. Supernovae on the other hand produce more metals than helium and hence are not helpful for generating a high helium-to-metal population.

2.3 The Maximum-AGB model

It has already been shown that a closed-box system cannot achieve such high values of helium and helium enrichment parameter as implied for the blue population of ω Cen (Choi & Yi 2007). This is mainly because of the ill effect of supernovae on $\Delta Y/\Delta Z$.

In realistic models for small potential wells, the remnants of supernovae are believed to escape the system (Larson 1974). Such explosions would probably remove the remnant gas in the potential as well after the first star formation episode. But in general, the escape of the supernova materials is likely to be easier than the escape of the remnant gas. So we set up *ad hoc* models in which the supernova ejecta escape the system without affecting the chemical properties of the remnant gas, hence maximising the chemical influence of AGB stars. We call this “the maximum-AGB models”.

Our prescription has two input parameters. The first free parameter, m_{esc} , indicates the critical mass above which the stellar mass ejecta escape the potential well without affecting the chemical abundance of the remaining gas. This parameter is likely a function of the mass of the system because the potential well determines whether the supernova-driven winds can escape the gravitational potential of the

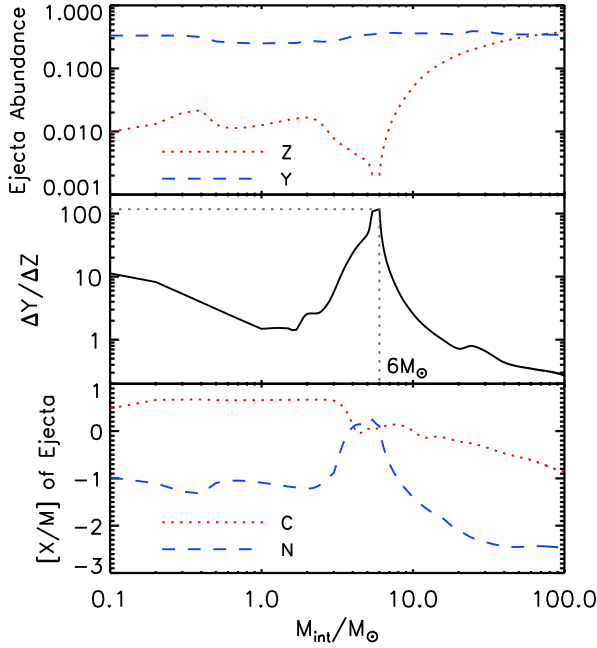


Figure 1. The theoretical ejecta abundance calculated from the stellar yields of Maeder (1992) and Herwig (2004). *Top:* The helium and metal abundances of the ejecta from the metal-poor ($Z = 0.001$) stars of mass $0.1 - 100M_{\odot}$. *Middle:* The resulting helium enrichment parameters. *Bottom:* The carbon and Nitrogen abundances of the ejecta from the stars with the initial compositions $[C/M] = 0.0$, $[N/M] = 1.0$ following Piotto et al. (2005).

system or not. Karakas et al. (2006) assumed that the system can retain the ejecta from the stars with $m \leq 6.5M_{\odot}$. We explore an expanded parameter space for $5M_{\odot} \leq m_{esc} \leq 99M_{\odot}$. The scenario of Karakas et al. is equivalent to our scenario with $m_{esc} = 6.5M_{\odot}$. The model with the largest m_{esc} represents the ordinary chemical evolution model which takes account of all the mass ejecta from stars when calculating the metallicity of the next generations. The model with the smallest m_{esc} shows the extreme condition that the ejecta from AGB stars dominates the chemical properties of the next generations, hence the maximum-AGB model. Then we define $E(t)$, the ejecta gas mass at time t as

$$E(t) = \int_{m_t}^{m_{esc}} dm \phi(m) (m - w_m) \psi(t - \tau_m), \quad (7)$$

and $E_Z(t)$, the mass of the ejected metal at time t as

$$E_Z(t) = \int_{m_t}^{m_{esc}} dm \phi(m) [mp_m \psi(t - \tau_m) + (m - w_m) \psi(t - \tau_m) Z_g(t - \tau_m)], \quad (8)$$

Another free parameter is R_{rMS} which indicates the mass ratio of the initial starburst i.e., for the former, red population of ω Cen to the total system mass. We assume that the formation of the former (red) population is essentially instant and regulate the fraction of the initial star formation by using the free parameter R_{rMS} . We calculate models for $0.5 \leq R_{rMS} \leq 1.0$. The model with $R_{rMS} = 1.0$ means all gas goes into the star formation at time $t = 0$ and the metallicity of the gas that forms the next generation

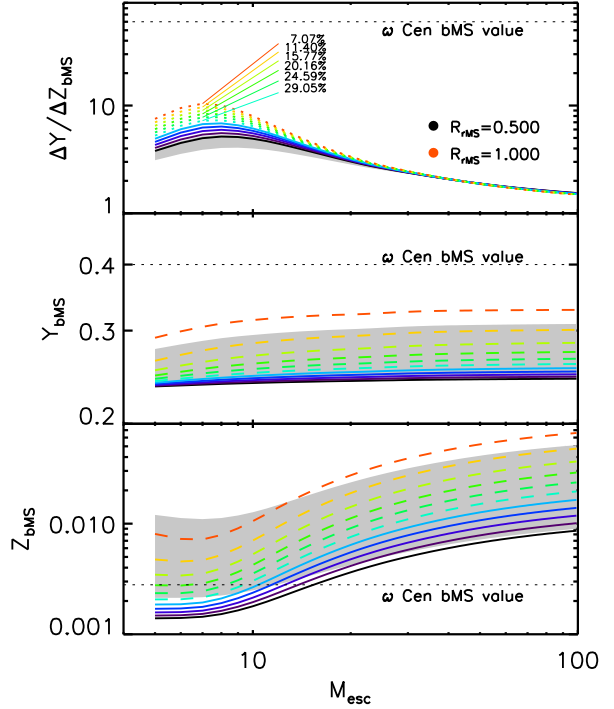


Figure 2. The chemical abundances of the second stellar generation resulting from the maximum-AGB chemical evolution model. The results are shown for different values of initial starburst mass fractions, $R_{rMS} = 0.5 - 1.0$ with $\Delta R_{rMS} = 0.05$. Dashed/solid lines show the models that are incompatible/compatible with the empirical mass fraction of the blue population (30 percent), for the age difference of 1 Gyr. The shaded region shows the results for the age difference of 3 Gyr. The chemical abundances of the blue population of ω Cen are shown by the black dotted horizontal line in each panel. *Top:* The helium enrichment parameter. The mass fractions of the blue population are shown for the models that are incompatible with the empirical requirement (30 percent). *Middle:* The helium content. *Bottom:* The metallicity.

of stars is solely influenced by the ejecta from the former generation. Then we define the star formation rate as

$$\psi(t) = R_{rMS} \delta(t) \quad (9)$$

where $\delta(t)$ is a Dirac delta function.

In effect we are testing a self-enrichment hypothesis where the helium enrichment of the blue population is solely due to the ejecta from the former (red) population. We calculate the gas enrichment history for the predicted age difference between the two extreme populations of ω Cen, i.e. 1 – 3 Gyr (Lee et al. 2005; Stanford et al. 2006). We also consider the observed number fraction of the bMS stars (~ 30 percent) as an additional constraint. The rMS-to-bMS ratio, 7:3, may not be a strong constraint if the bMS and rMS populations formed in geographically different regions. For example, the bMS stars are observed to be more centrally concentrated than the rMS stars (Sollima et al. 2007), and thus if one assumes that the original rMS stars had a better chance of escaping from the system potential during the dynamical encounters with the Milky Way galaxy over the

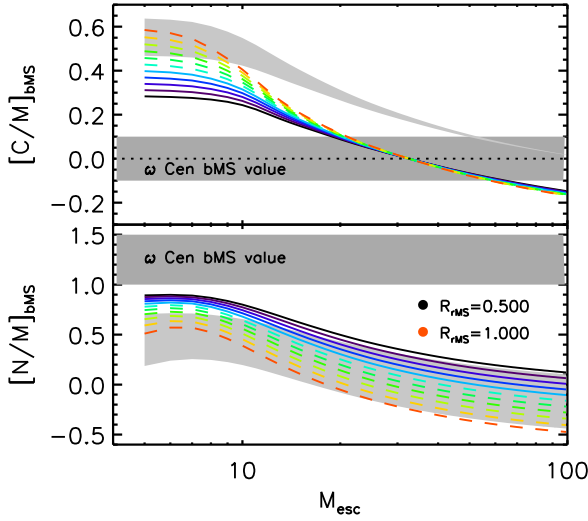


Figure 3. The same as Figure 2, but for the spectroscopic measurements $[C/M]$ (top) and $[N/M]$ (bottom).

Hubble time, the original mass ratio may have been higher. We discuss the impact of this uncertainty in §3.

3 RESULTS

Figure 2 shows the helium and metal contents and the helium enrichment parameter of the remaining gas after a 1-Gyr evolution. The chemical properties of the models are presented for our $m_{esc} - R_{rMS}$ parameter space. The models assuming $\Delta t \sim 1$ Gyr (that is, the age difference between the old red and the young blue populations) are shown by lines, while the shaded region shows the results for $\Delta t \sim 3$ Gyr which is close to the upper limit on the age difference between the two populations (Stanford et al. 2006). The solid/dashed lines show the models that are compatible/incompatible with the observed mass ratio, 7:3, respectively. As shown in the top panel of Fig 2, the model with $m_{esc} = 7M_{\odot}$ and $R_{rMS} = 1.0$ has the largest value of $\Delta Y/\Delta Z \sim 10.5$. This value is much higher than the canonical value, $\Delta Y/\Delta Z \sim 2$ (Pagel & Portinari 1998) yet still much lower than the value we are seeking for (i.e., $\Delta Y/\Delta Z \sim 70$). In addition, the maximum helium content which can be achieved in this model is $Y \sim 0.33$ (for $m_{esc} \geq 50M_{\odot}$ and $R_{rMS} = 1.0$), also much smaller than $Y \sim 0.4$ estimated by the CMD analysis of ω Cen. Even when we assume an extreme condition, $m_{esc} = 5M_{\odot}$, that is hardly plausible in terms of physics, the extremely high values of helium and helium enrichment parameter suggested for the bMS cannot be reproduced.

As mentioned in §2, the mass fraction of the bMS population (30 percent) may be an upper limit. As seen in the top and middle panels of Figure 2, models cannot reach the required values even when we lower the bMS mass fraction constraint by a significant factor. The situation becomes even worse when we compare the models to the spectroscopic line strengths. In Figure 3, we present the resulting carbon and nitrogen contents of the models for the same

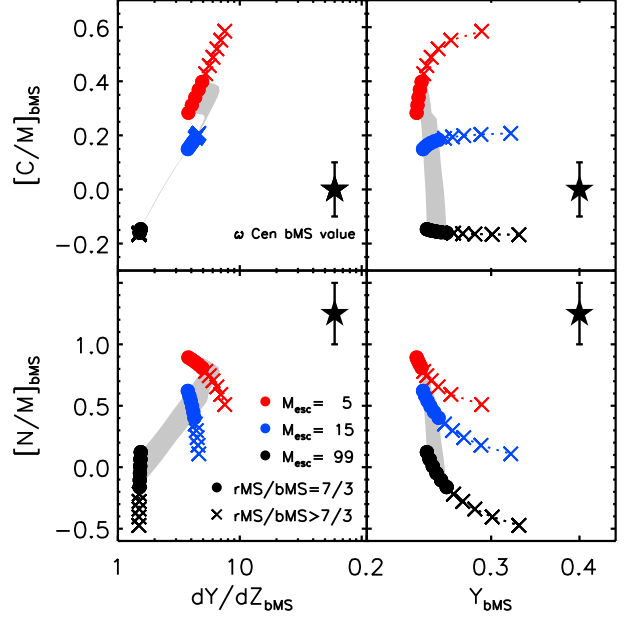


Figure 4. The calculated chemical abundance of the ejecta for the entire ($R_{rMS} = 0.5 \sim 1.0$, $\Delta R = 0.05$) parameter spaces of the maximum-AGB model is represented. Filled circle and cross represents the resulting value of $m_{esc} = 5, 15, 99M_{\odot}$ model. Filled circle indicates that the condition of mass ratio between rMS and bMS is satisfied while cross denotes the model which do not meet this condition. Shaded region shows the viable region of the total parameter space, $m_{esc} = 5 - 99M_{\odot}$, which satisfies the mass ratio condition. Reference values of blue population of ω Cen are marked (filled star) in each panel.

m_{esc} and R_{rMS} parameter space as in Figure 2. This result is important since the reference chemical properties of the bMS are directly measured *via spectroscopy*, while the helium abundance and the helium enrichment parameter are *deduced* from CMD fits. The models with $m_{esc} \approx 7M_{\odot}$ show the largest value of $\Delta Y/\Delta Z$ (Figure 2 top panel) but do not match the observed carbon content of the bMS (Figure 3 top panel). The horizontal, shaded band shows the observed value for the bMS stars (Piotto et al. 2005). However, the errors are not given and can be more significant than we estimated from the literature (Piotto et al. 2005; Stanford et al. 2007). In case of the red population, $[N/M]$ is poorly constrained; Piotto et al. (2005) mentioned that values of $[N/M] \leq 1.0$ could also be compatible. We set $[N/M] = 1$ for the red population. This assumption on the nitrogen abundance of the rMS population may appear unphysically high considering the typical nitrogen production of stars, that is, an order of $[N/M] \sim -1$ through 0, as shown in Figure 1. The use of lower values of $[N/M]_{rMS}$ results in a substantially greater mismatch in $[N/M]_{bMS}$ in this figure.

We present the resulting carbon, nitrogen and helium abundances simultaneously in Figure 4. The three cases of $m_{esc} = 5, 15, 99M_{\odot}$ are shown. Filled circle (cross) show the models that are consistent (inconsistent) with the mass ratio constraint, respectively. The shaded region shows the parameter space that satisfies the mass ratio constraint. The observed chemical properties of the blue population stars of

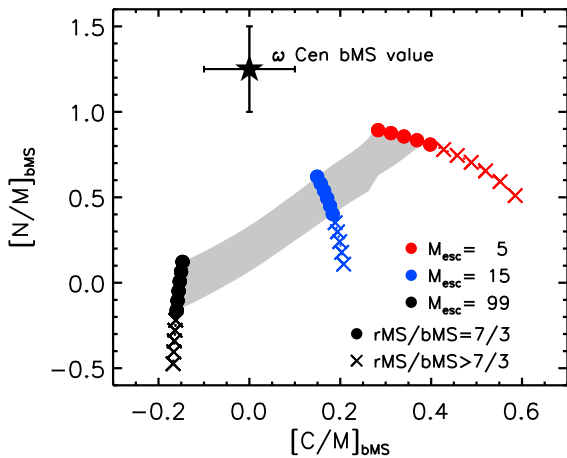


Figure 5. The same as Figure 4 but for the $[C/M]$ and $[N/M]$ space.

ω Cen (filled star in each panel) are not reproduced under any circumstance. Note the logarithmic scale of the axes.

Figure 5 shows that the models fail to match the *spectroscopic* data of Piotto et al. (2005). The empirical value (star symbol with errors) measured using the VLT is in reasonable agreement with the more recent measurements of Stanford et al. (2007). As mentioned, the models are based on the assumption of $[C/M] = 0.0$ and $[N/M] = 1.0$ for the red population. The model values of $[N/M]_{bMS}$ may be considered upper limits. The mismatch is significant.

4 DISCUSSION

We have used a chemical enrichment model to demonstrate that the AGB ejecta of the red population cannot have produced the blue population of ω Cen. We tested a hypothesis in which the massive star ejecta escape the potential well so that the AGB effect can be maximised. But even in this *ad hoc* scenario, models miserably fail to match the chemical properties of the blue population of ω Cen. We use the bMS mass fraction (30 percent) and the age difference between the two populations (1–3 Gyr) as constraints, but changing them does not make the match any better. We as a result confirm the result of Karakas et al. (2006).

The helium content of the AGB ejecta is basically too small to be consistent with the value suggested for the blue population of ω Cen, $Y \sim 0.4$, as we discussed earlier (Choi & Yi 2007). Romano et al. (2007) has also confirmed this using various yields from independent studies (e.g. van den Hoek & Groenewegen 1997; Meynet & Maeder 2002; Hirschi 2006; Meynet, Ekstrom, & Maeder 2006). Such a high level of helium excess can be achieved only through massive stars (Norris 2004; D’Antona et al. 2005; Maeder & Meynet 2006). However, such massive stars also produce a large amount of metals and thus resulting in a small value of $\Delta Y/\Delta Z$ (Choi & Yi 2007). In this respect, a variation in the initial mass function is useless. The escape of the massive star ejecta through supernova-driven winds would lead to a larger $\Delta Y/\Delta Z$ roughly up to 10; yet,

still much lower than suggested by the CMD fits. Even if we admit that the estimation for the helium abundance via CMD fits is extremely difficult and so uncertain, the maximum-AGB scenario cannot reproduce the carbon and nitrogen properties spectroscopically observed and hence probably more robust, either.

For an alternative solution, surface pollution scenarios (Tsujiimoto, Shigeyama, & Suda 2007; Newsham & Terndrop 2007) have been suggested and deserve attention especially because they demand only mildly-enhanced helium abundance for the blue population. From a different avenue, Chuzhoy (2006) suggested that the primordial helium may have been concentrated in stellar-mass scales within minihalos of size roughly consistent with dwarf galaxies. This aspect is particularly appealing because ω Cen is often considered as a remnant of a former dwarf galaxy and the multiple main sequences are found in the most massive globular clusters in general. This scenario offers an attractive solution to the helium variation in *first* stars. However, it remains unclear how long the extreme-helium clumps could last. The blue population of ω Cen appears to be substantially enhanced in metals as well and hence hardly qualifies as first stars and younger than the red population by a couple of billion years. Choi & Yi (2007) proposed the fluctuation in the chemical properties of the initial starburst clumps during and after the first star formation epoch. Given the impact of the issue to the understanding of the galaxy formation, a more detailed and realistic model calculation is necessary until such scenarios become convincing.

ACKNOWLEDGMENTS

We are grateful to Ignacio Ferreras, Leonis Chuzhoy, Young-Wook Lee, Hansung Gim for useful comments.

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